U(1)′ instead of R-parity

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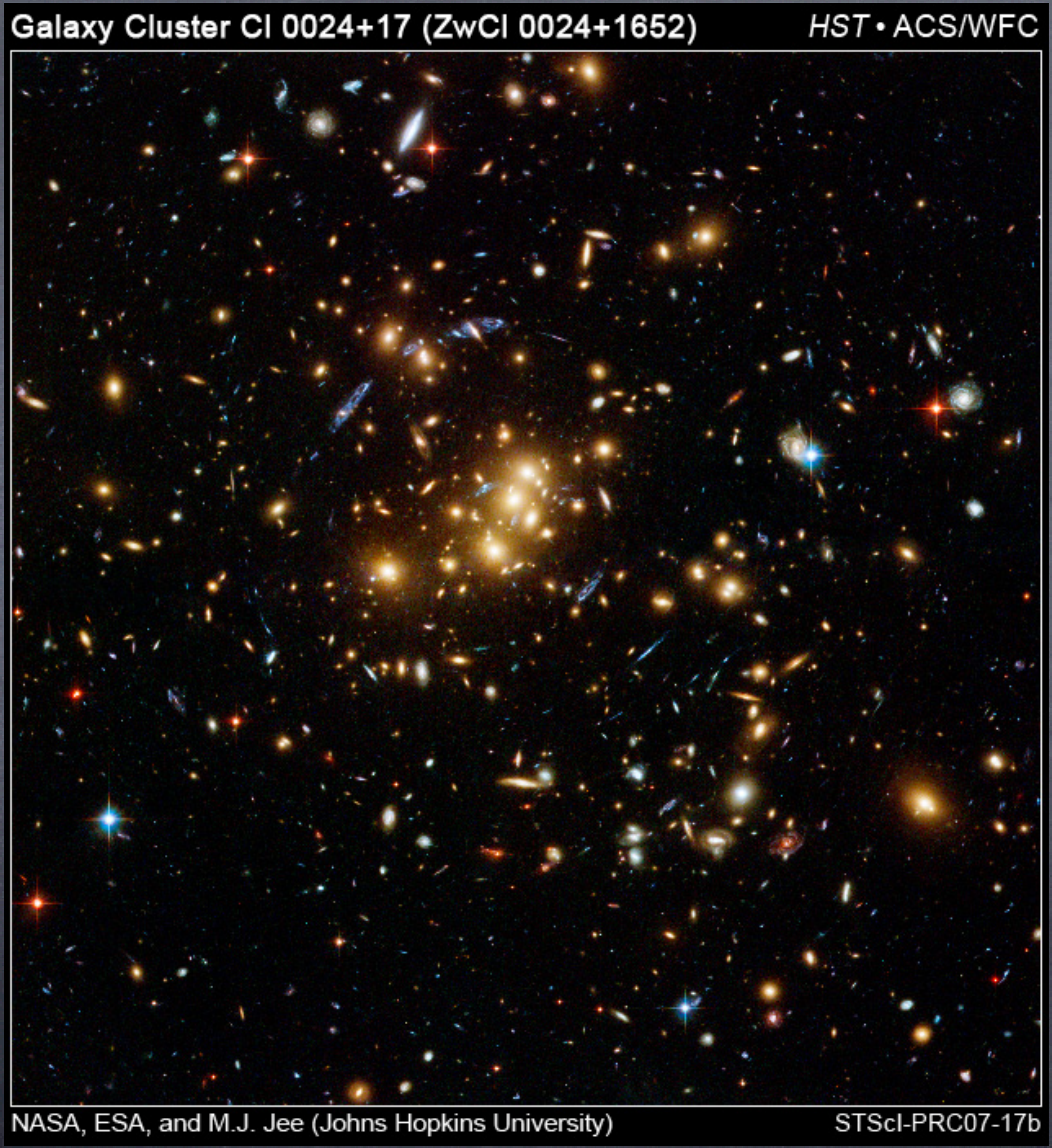
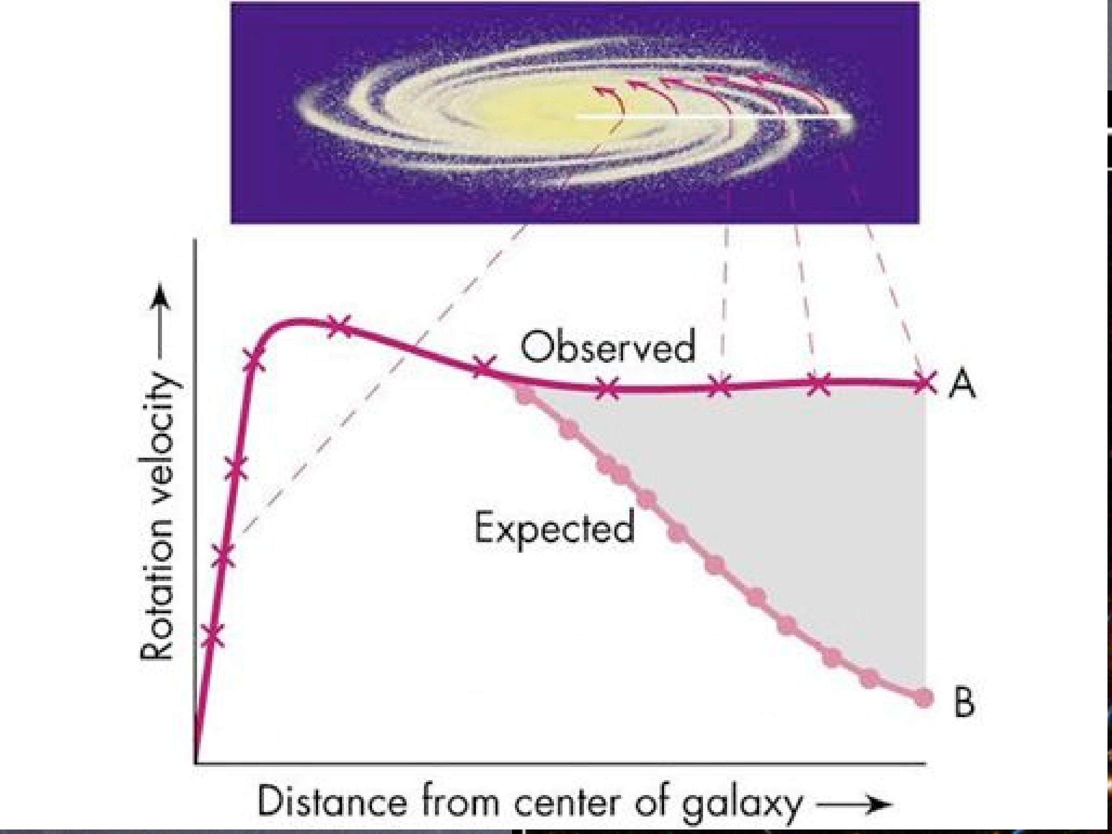
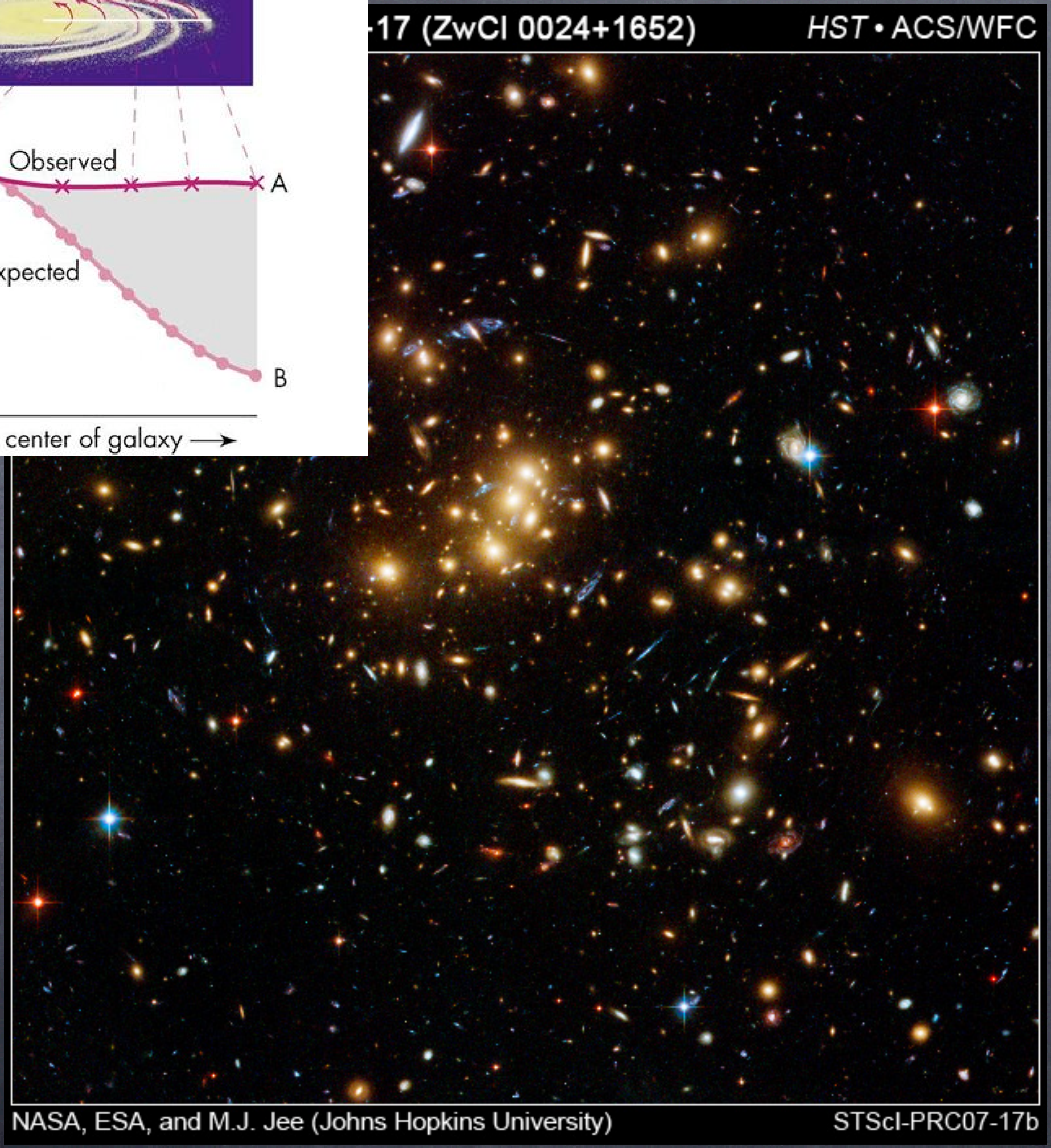
Seminar at BNL (8/7/2009)


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b


Observed
A
Expected
B
Rotation velocity ⟶
Distance from center of galaxy ⟶


-17 (ZwCl 0024+1652)
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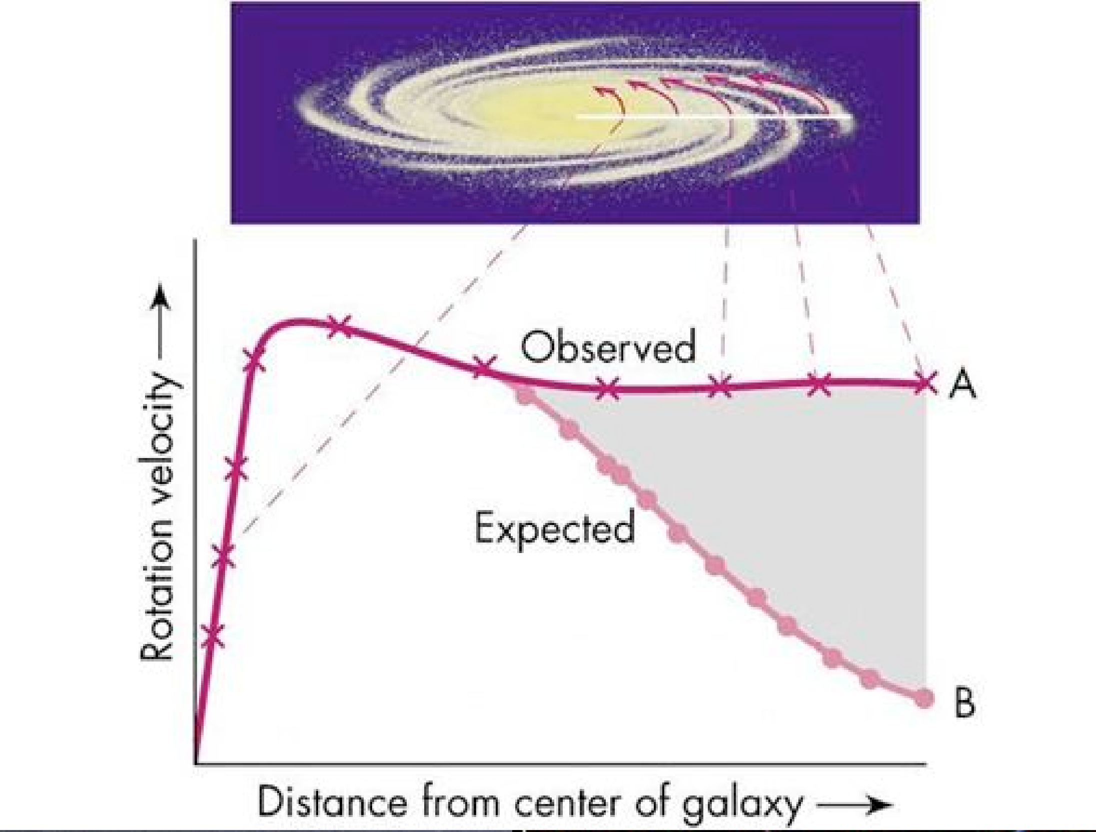
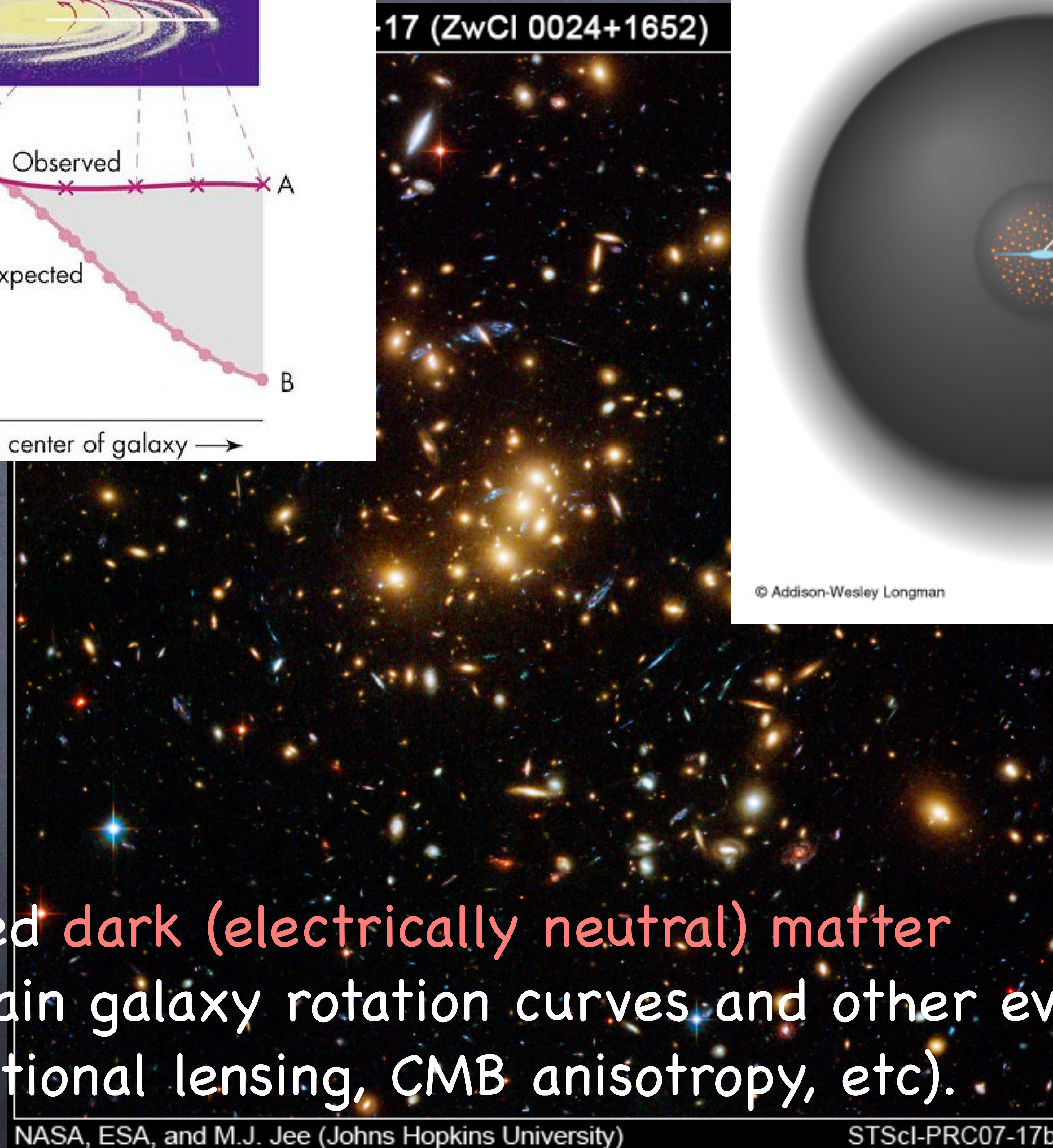
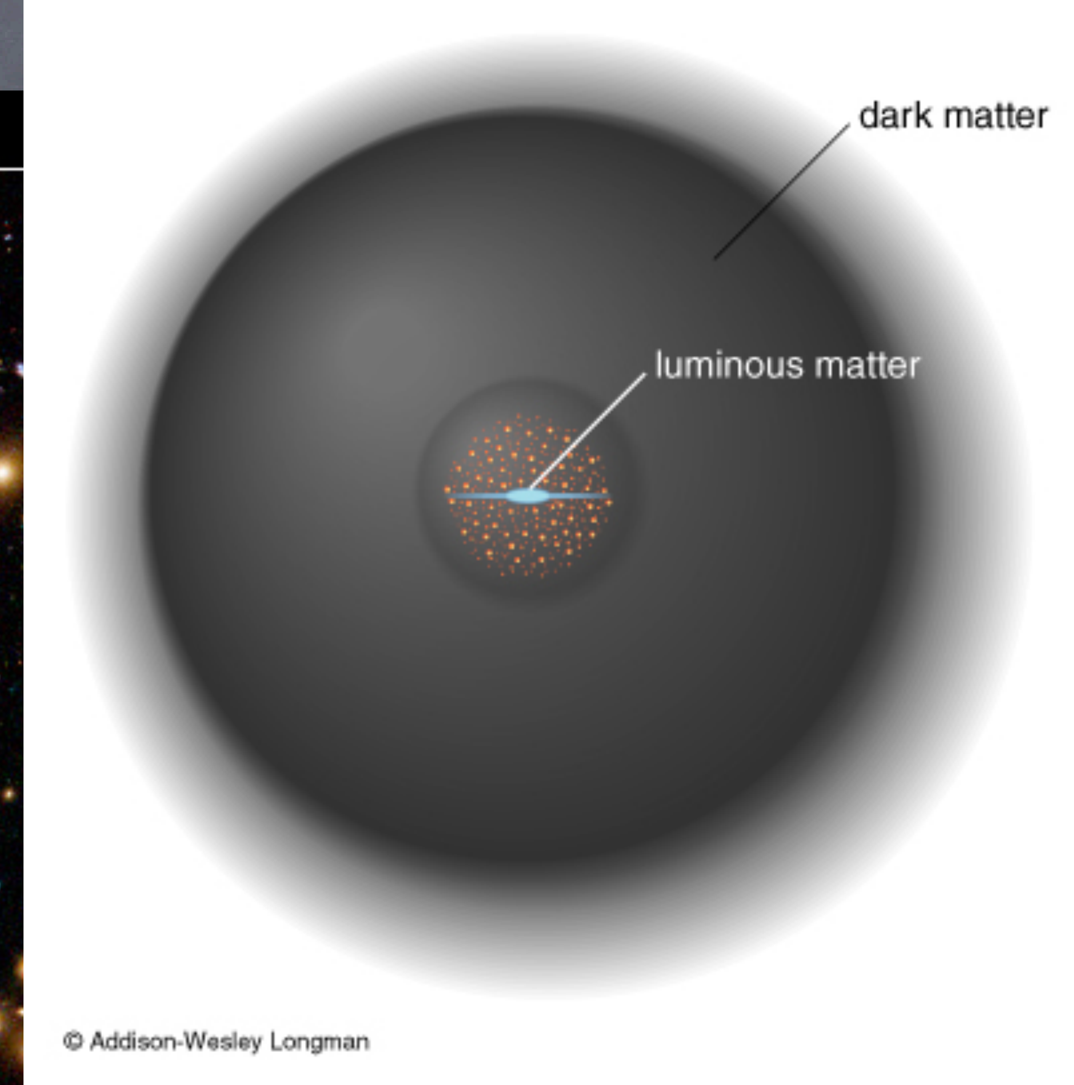






We need dark (electrically neutral) matter
to explain galaxy rotation curves and other evidences
(gravitational lensing, CMB anisotropy, etc).


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
Universe = Bright world + Dark world
(proton, etc) (dark matter)
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

Under Supersymmetry (SUSY),
proton and dark matter candidate decay rapidly.

Observation says
they should be extremely long-lived.

Q: What stabilizes them?
- Popular candidate: R-parity
- Alternative: U(1)′ gauge symmetry

Outline

Under Supersymmetry (SUSY),
proton and dark matter candidate decay rapidly.

1. SUSY needs a companion symmetry.

Observation says
they should be extremely long-lived.

Q: What stabilizes them?

2. What is R-parity?

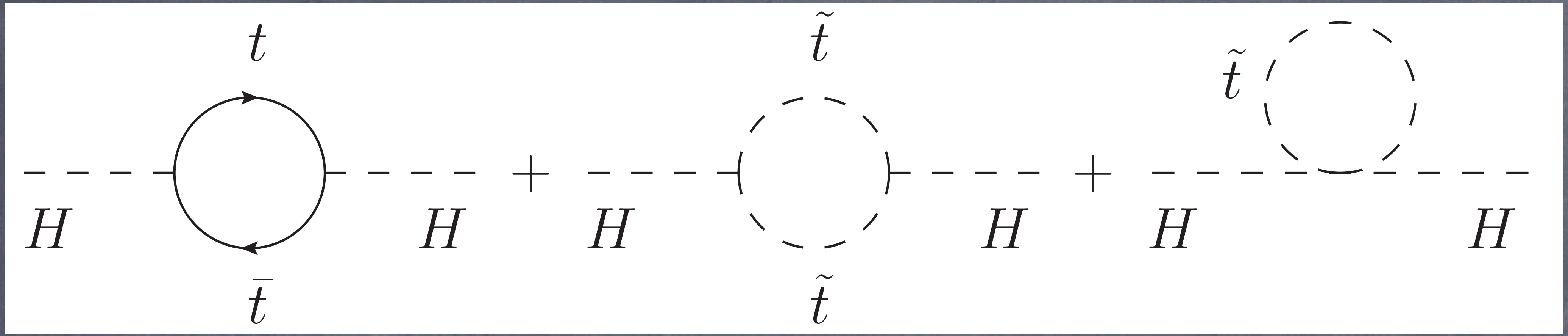
- Popular candidate: R-parity
- Alternative: U(1)′ gauge symmetry

3. What kind of U(1)′ can replace R-parity?

4. (Briefly) What are implications of U(1)′ for LHC?

1. Why SUSY and its companion symmetry?

Supersymmetry to protect Higgs mass



$$
\begin{aligned}
\delta m_H^2(\text{top} + \text{stop}) &= \left(-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots\right) + \left(\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots\right) \\
&= -\frac{9}{8\pi^2}\lambda_t^2 m_{\tilde{t}} \log\frac{\Lambda}{m_{\tilde{t}}} + \cdots
\end{aligned}
$$

"Higgs (spin 0 particle) mass can be protected by supersymmetry."

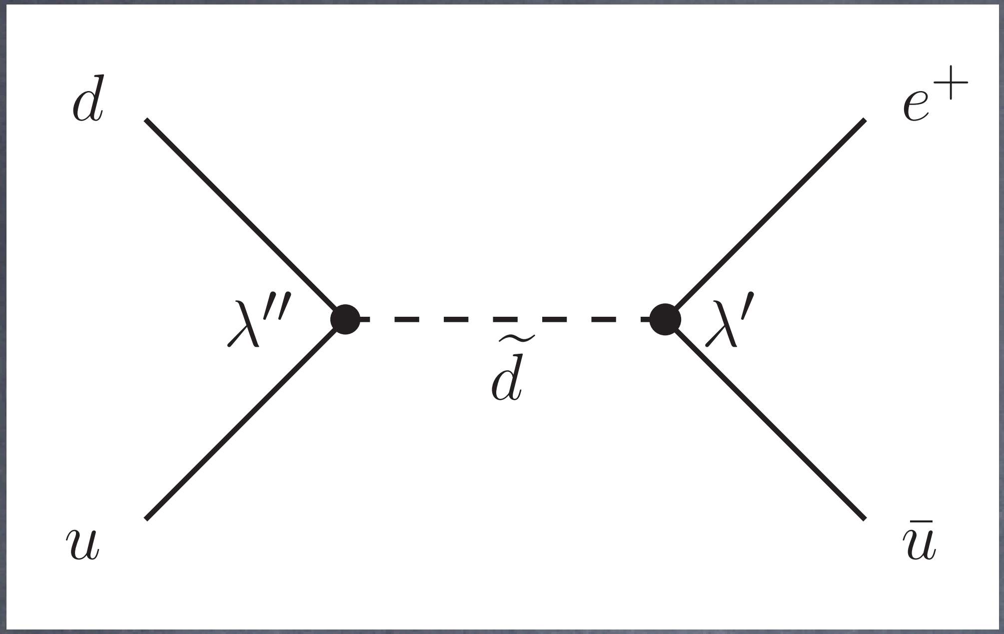
Spin 1/2 particle mass is protected by chiral symmetry.
Spin 1 particle mass is protected by gauge symmetry.

General SUSY

$$
\begin{aligned}
W &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c \\
&+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

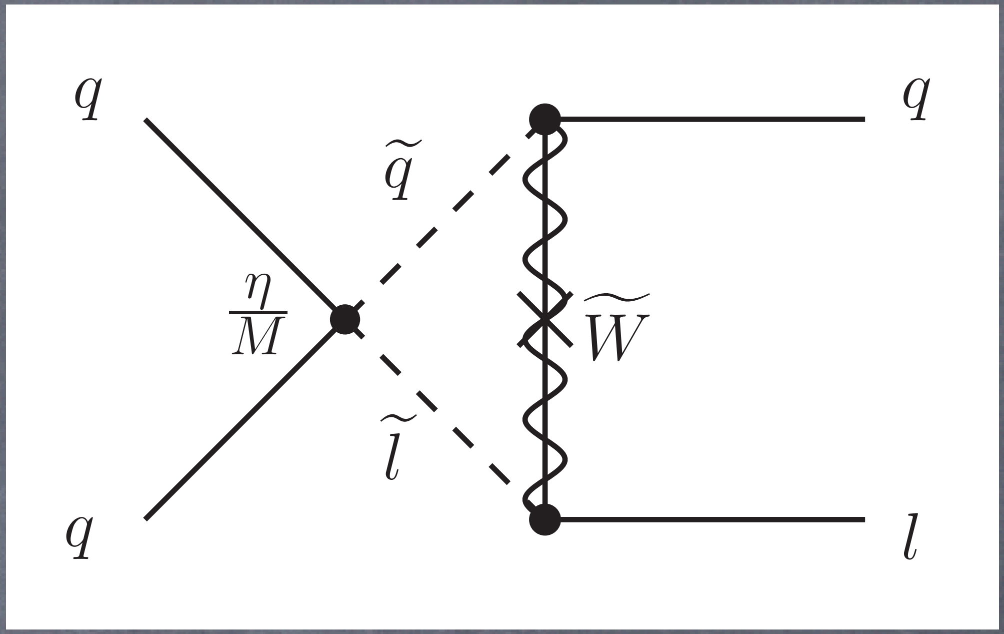
- Lepton number (L) and/or baryon number (B) violating terms at renormalizable and non-renormalizable levels:
  - one of the most general predictions of SUSY.
  - also source of problems.

Proton decay



[Dim 4 L viol. & Dim 4 B viol.]

$\lambda LLE^c + \lambda' LQD^c$ & $\lambda'' U^c D^c D^c$



[Dim 5 L&B viol.]

$$\frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c$$

To satisfy proton lifetime > 10^{29} years,

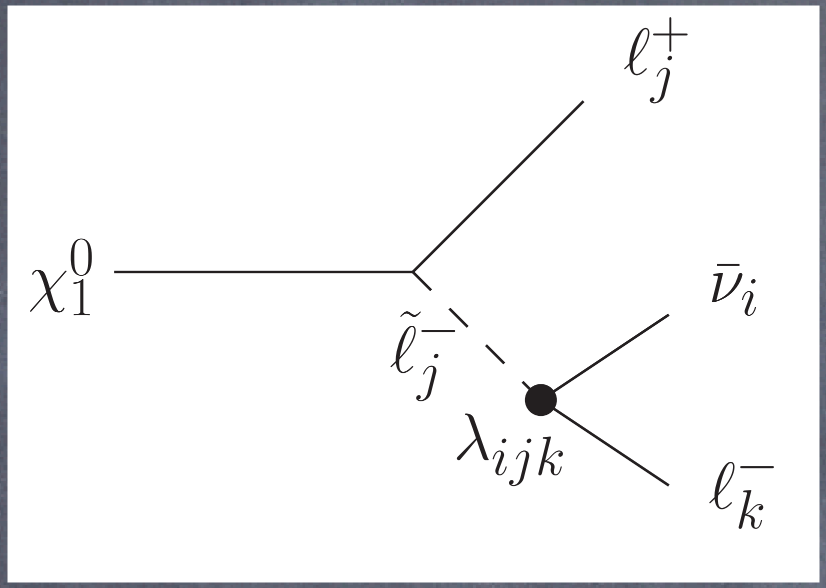
$$|\lambda_{LV} \cdot \lambda_{BV}| < 10^{-27}$$

(if one is 0, the other can be large)

$$|\eta| < 10^{-7}$$

(for $\Lambda = M_{Pl}$)

Dark matter candidate decay (lightest neutralino)



$$\Gamma = \lambda_{ijk}^2 \frac{\alpha}{128\pi^2} \frac{m_{\chi^0}^5}{m_{\tilde{f}}^4}$$

(ex: for χ~photino)

To be a viable dark matter, lifetime > Universe age (14 x 10^9 years)

$$|\lambda_{LV}|,\ |\lambda_{BV}| < 10^{-20}$$

Dark matter candidate

(to form galaxies and their clusters)

- A viable dark matter candidate should
  - be Cold (non-relativistic), Neutral, Stable.
  - explain relic density (WMAP, SDSS) : 23% of total energy density.
  - satisfy direct detection experiments limit (CDMS, XENON, etc.).

SM: neutrino ($m_\nu < 0.1$eV) is neutral and stable,
but relativistic.

SUSY: neutralino (superpartner of neutral Higgs and gauge boson) is
neutral and heavy (therefore, cold).
-> Dark matter candidate if stable

SUSY needs a companion mechanism or symmetry.
(for stability of proton and dark matter)

2. R-parity

: Most popular SUSY companion symmetry

LSP dark matter

R-parity

SM particles	R_p=even
Superpartners	R_p=odd

Lightest superpartner (LSP) is stable under R-parity.

Neutralino is a good DM candidate if it is LSP.

Proton stability under R-parity

$$
\begin{aligned}
W &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \xcancel{\lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c} \\
&+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

- over-constraining of R-parity: All renormalizable L violating and B violating terms are (unnecessarily) forbidden.
- under-constraining of R-parity: Dim 5 L&B violating terms still mediate too fast proton decay. Weinberg [1982]

Look for an alternative

R-parity may be still valid, but possibilities are limited.
(ex) What if B/L violating signals are found?

Find an alternative SUSY companion symmetry, which can

- allow B or L violating terms
- address proton stability (including non-renormalizable operators)
- address dark matter issue (non-LSP dark matter)

3. TeV scale U(1)′ gauge symmetry

3. TeV scale $U(1)'$ gauge symmetry

alternative to R-parity
for p&DM stability

Remnant discrete symmetry of U(1)′

Z_N emerges from U(1)′ naturally (after S gets vev).

$$N = z[S]$$
$$q[F_i] = z[F_i] \bmod N$$

($q[F_i]$: Z_N charge, $z[F_i]$: U(1)′ charge of each field F_i)
after integer normalization of charges

S: Higgs singlet that breaks U(1)′ spontaneously

Our model

HL, Luhn, Matchev [2007~2008]

$$U(1)' \to Z_6 = B_3 \times U_2$$

B_3 (Baryon triality): stabilizes proton

U_2 (U-parity): stabilizes hidden sector DM candidate

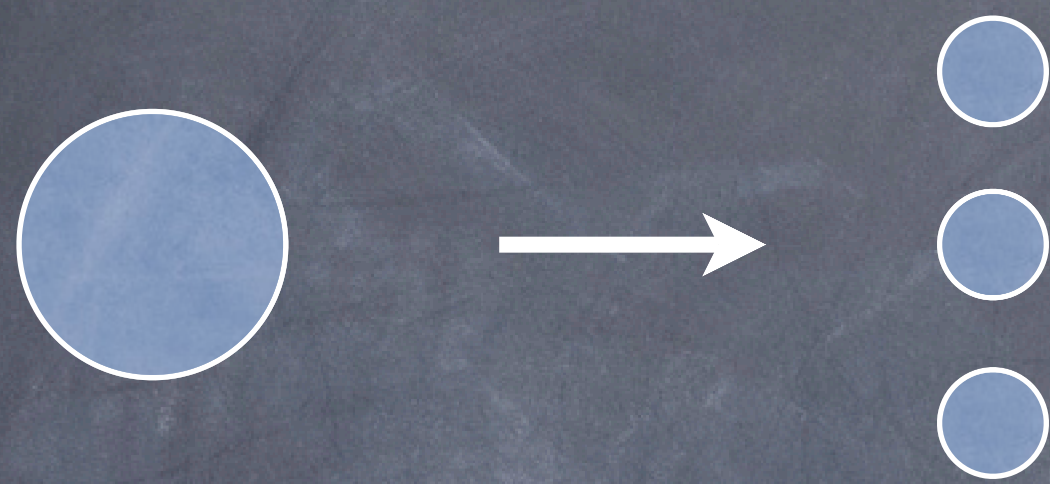
B_3 (Baryon triality)

Ibanez, Ross [1992]

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning
B_3	0	-1	1	-1	-1	0	1	-1	$-B+y/3$

- B_3 selection rule: $\Delta B = 3 \times$integer
  - L is freely violated.
  - B can be violated only by $3 \times$integer.

Stable proton under B_3

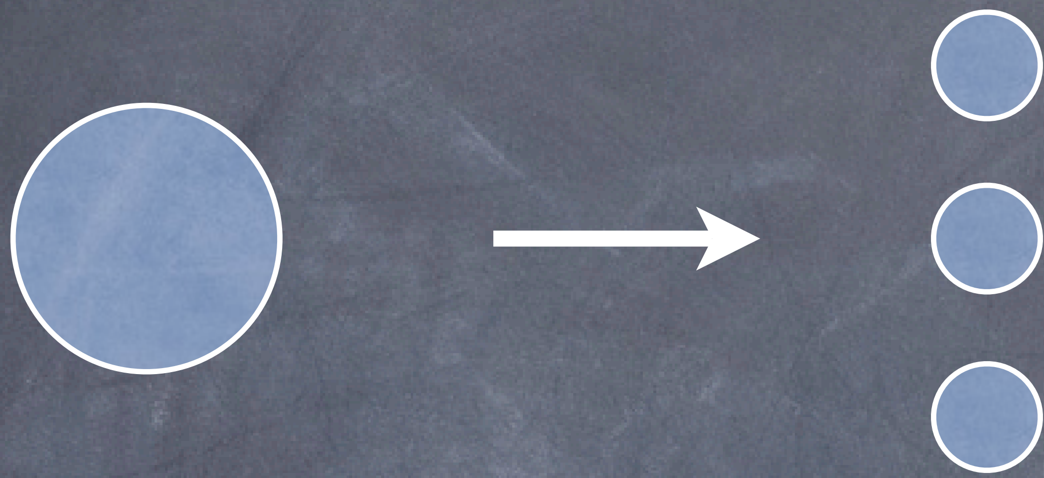


lightest baryon
[Total B=1]

non-baryons
[Total B=0]

Proton decay ($\Delta B=1$) is forbidden by B_3 ($\Delta B=3\times$integer).

Stable proton under B_3



pion (B=0)

electron (B=0)

. . .

proton (B=1)

lightest baryon
[Total B=1]

non-baryons
[Total B=0]

Proton decay ($\Delta B=1$) is forbidden by B_3 ($\Delta B=3\times$integer).

Proton stability better than R-parity

What about dark matter?

Hidden sector fields (SM singlet exotics): interact only with $U(1)'$, often necessary for anomaly cancellations with $U(1)'$.
($[\text{gravity}]^2$-$U(1)'$ and $[U(1)']^3$)

(ex) $W_{hid} = SXX$

They are neutral and massive.
Good DM candidate if stable.

LUP dark matter

Hur, HL, Nasri [2007]

U(1)′ itself can stabilize the hidden sector fields.
Best way to see this: invoke Z_2 as a subgroup of U(1)′

U-parity

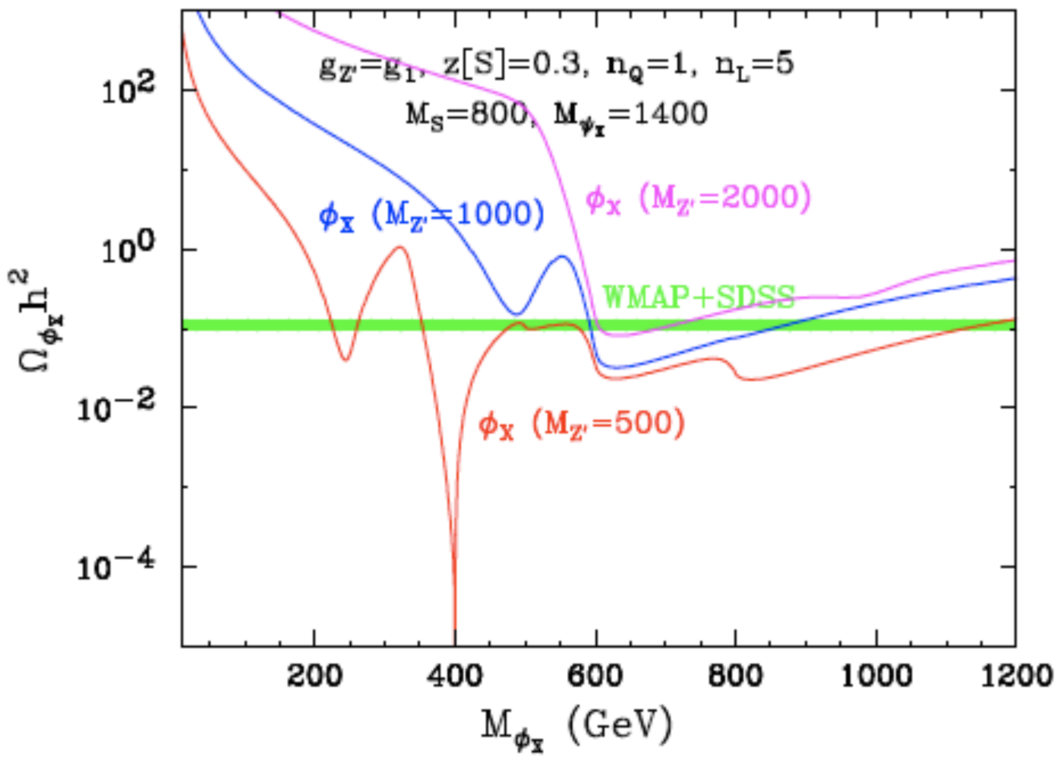
MSSM particles	U_p=even
Hidden sector particles	U_p=odd

Lightest U-parity odd particle (LUP),
either fermion or scalar, is stable under U-parity.

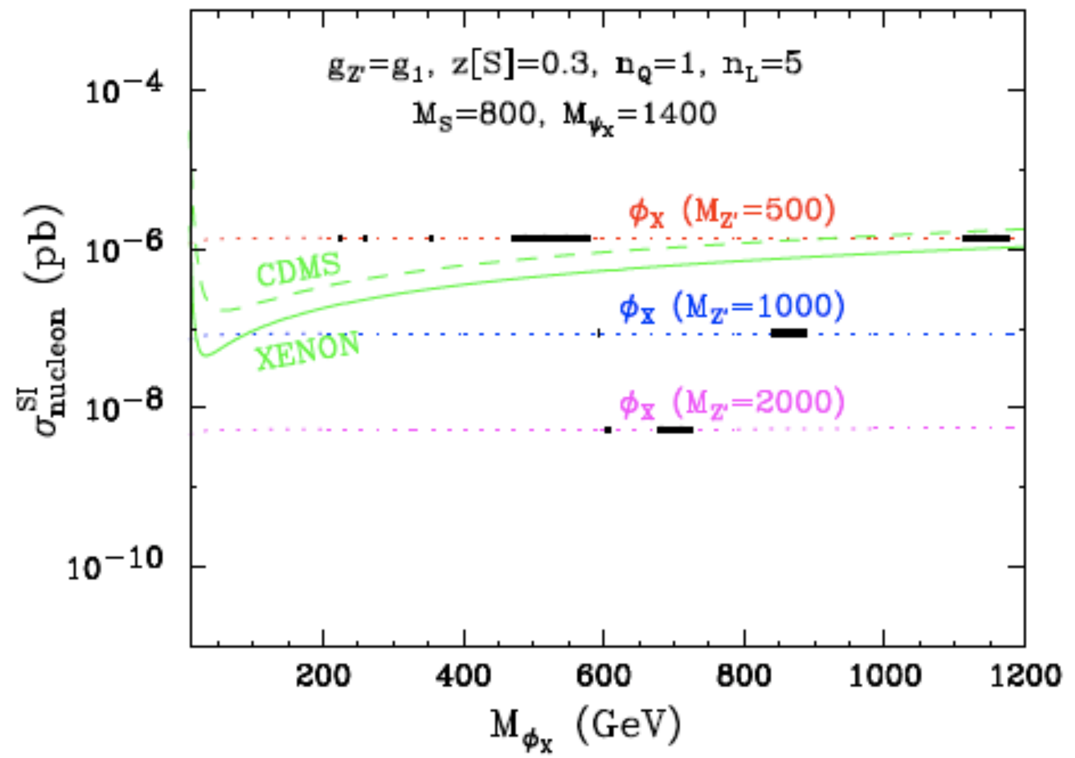
LUP is a good DM candidate.

Relic density and Direct detection

- X X -> f $\bar{f}$ (mediated by Z')
- X X -> $\tilde{f}$ $\tilde{f}$* (mediated by Z', S)
- . . .



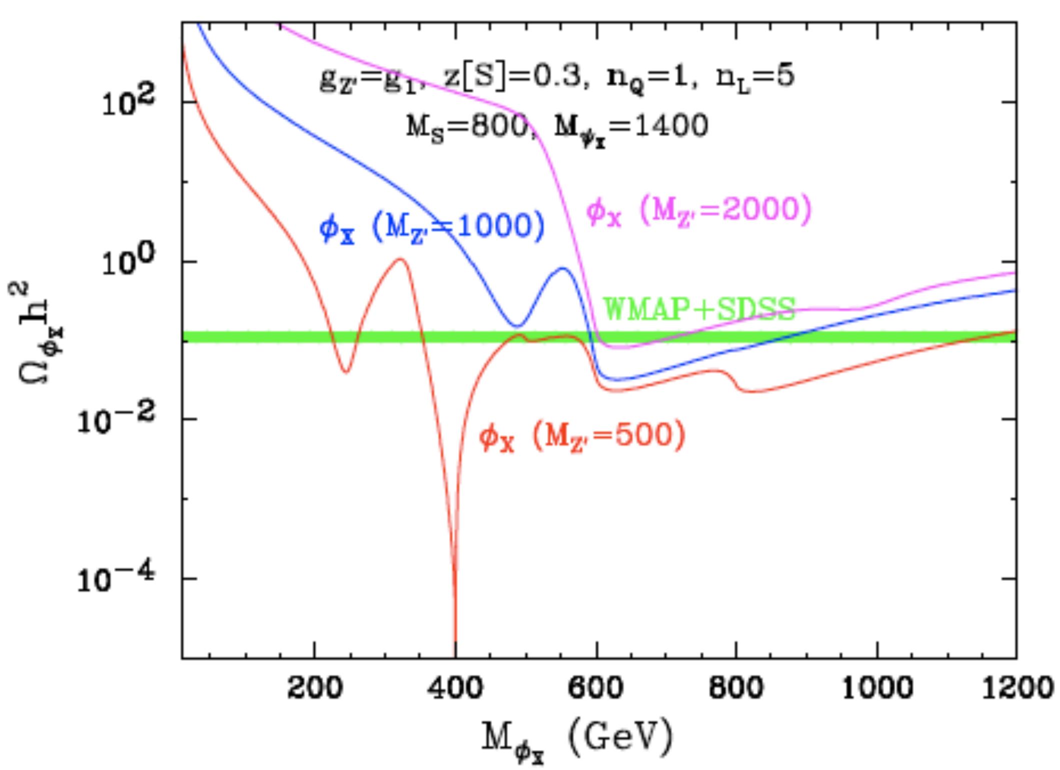
[Relic density]



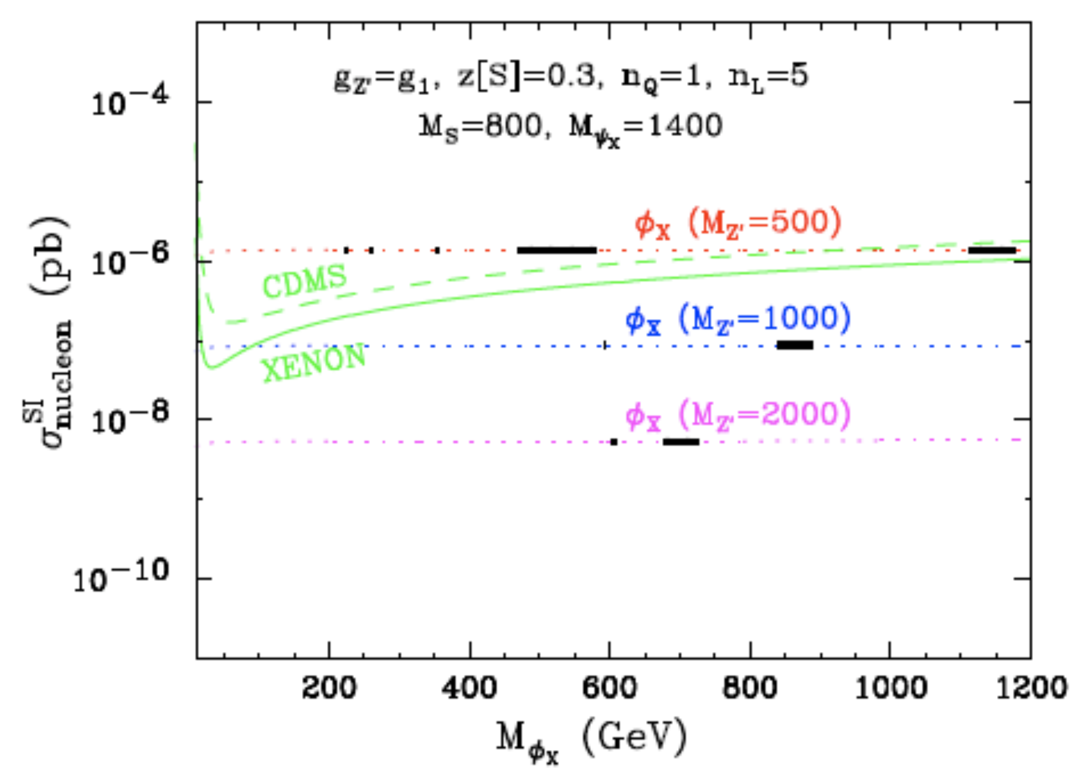
[Direct detection]

Relic density and Direct detection

- X X -> f $\bar{f}$ (mediated by Z′)
- X X -> $\tilde{f}$ $\tilde{f}$* (mediated by Z′, S)
- . . .



[Relic density]

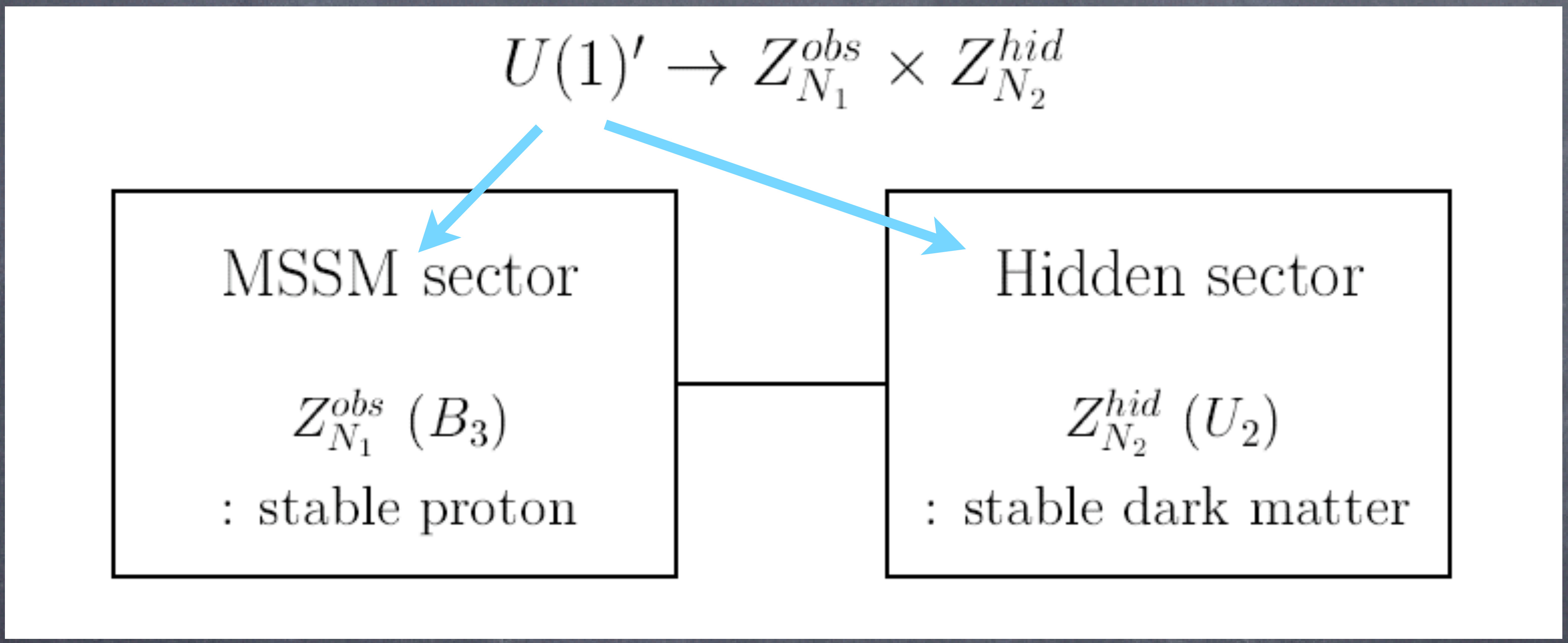


[Direct detection]

LUP: viable DM candidate

Unified picture of stabilities in the observable and hidden sectors

[U(1)′ interacts with both sectors]



A single U(1)′ gauge symmetry provides stabilities for proton (MSSM sector) and dark matter (Hidden sector).

Additional advantage of U(1)′: μ-problem

$$
\begin{aligned}
W &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c \\
&+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

$\mu \approx O(EW)$ to avoid fine-tuning in the EWSB.

Why is $\mu \not\approx O(\Lambda)$? (μ-problem) Kim, Nilles [1984]

U(1)′ can solve the μ-problem.

Natural scale of U(1)′ in SUSY is TeV ($\because$ sfermion masses).

$W = S H_u H_d$ -> $\mu_{eff} = \langle S \rangle \approx O(EW/TeV)$

How to get $Z_6=B_3\times U_2$ out of $U(1)'$

HL, Luhn, Matchev [2007]; Hur, HL, Luhn [2008]

How to get $U(1)' \to B_3 \times U_2$

In the minimal fields assumption of

$$N_{\text{Higgs pair}} = 1, \quad N_{\text{fermion family}} = 3, \quad N_{SU(2)_L \text{ exotics}} = 0$$

1. Solve the μ-problem with $U(1)'$ gauge symmetry (SH_uH_d).
2. Require $\mathcal{L}$ violating terms such as λLLE^c .
3. Require SXX term (TeV scale mass for hidden sector particle X).

Then $B_3 \times U_2$ is **automatically invoked**, and the proton and LUP are stable.

Recap: R-parity vs. U(1)′ in SUSY

	R-parity	U(1)′ -> $B_3 \times U_2$
proton	stable (for renormalizable terms)	stable (B_3)
dark matter	stable LSP	stable LUP (U_2)
μ-problem	not addressed	solvable

- TeV scale U(1)′ is a viable alternative to R-parity for a SUSY companion symmetry.

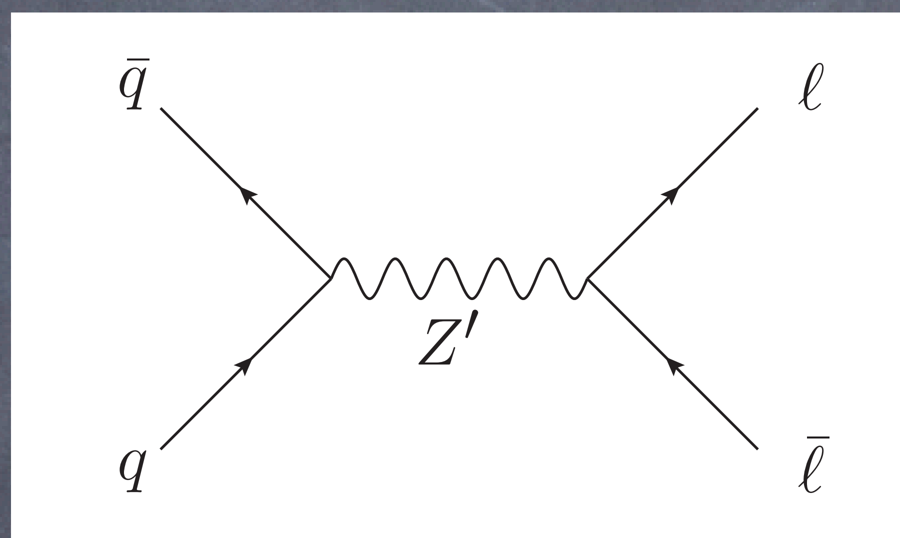
Same SUSY, but different SUSY companion symmetries
-> Distinguishable LHC predictions

4. LHC implications
of TeV scale U(1)′

TeV scale Z′ gauge boson

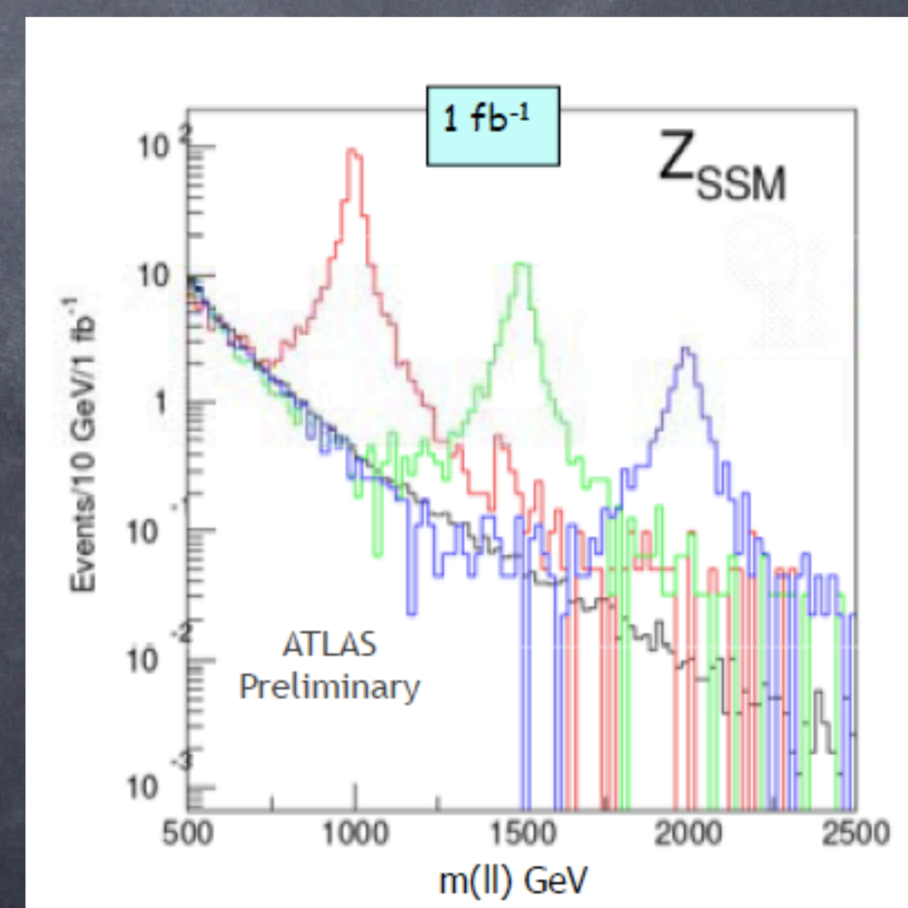
Motivation order: Higgs -> SUSY -> TeV scale U(1)′

TeV scale Z′



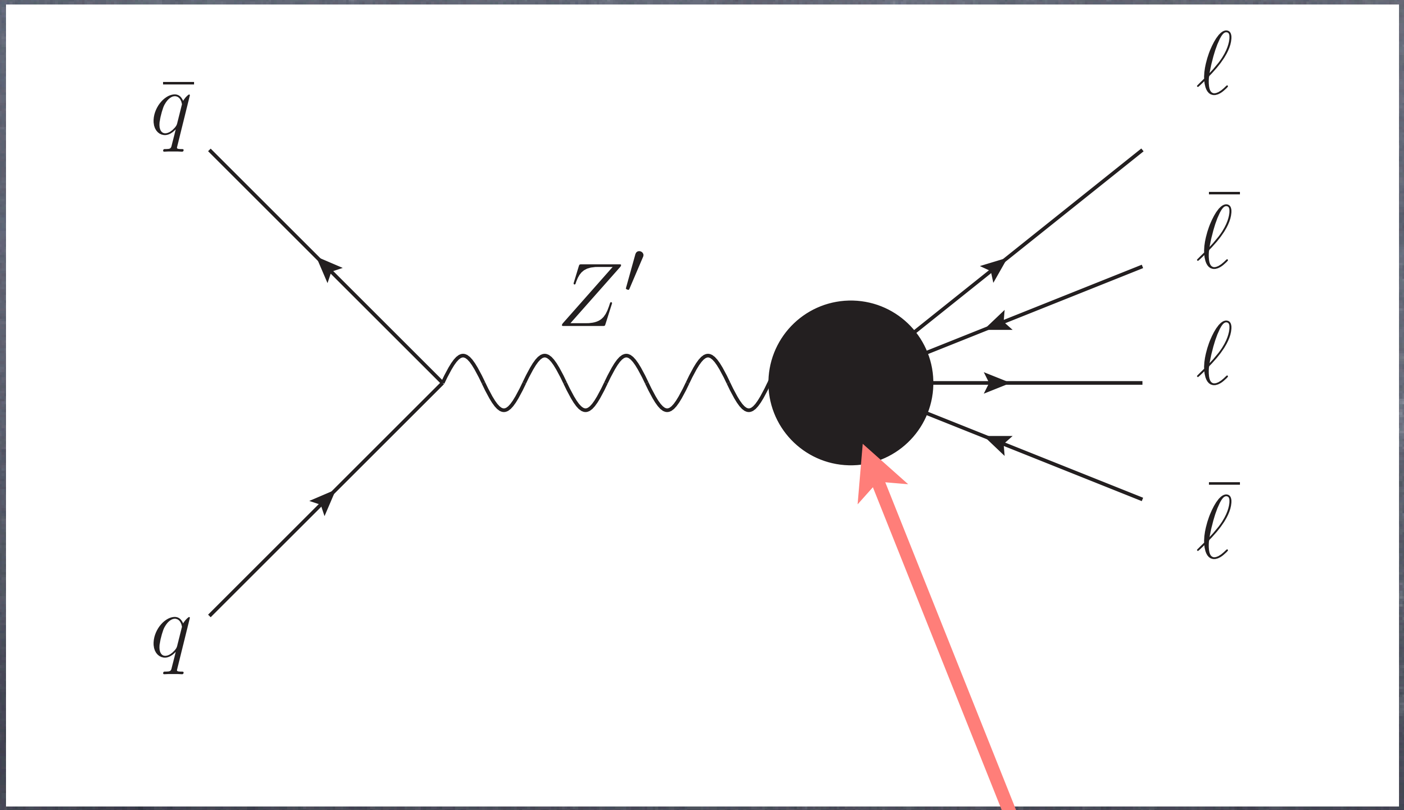
Dilepton Z′ resonance is very likely
first discovery at LHC because of
(i) enhanced cross section
(ii) clean leptonic signal

(Irreducible BKG for leptonic resonance is small.)



Our approach for LHC

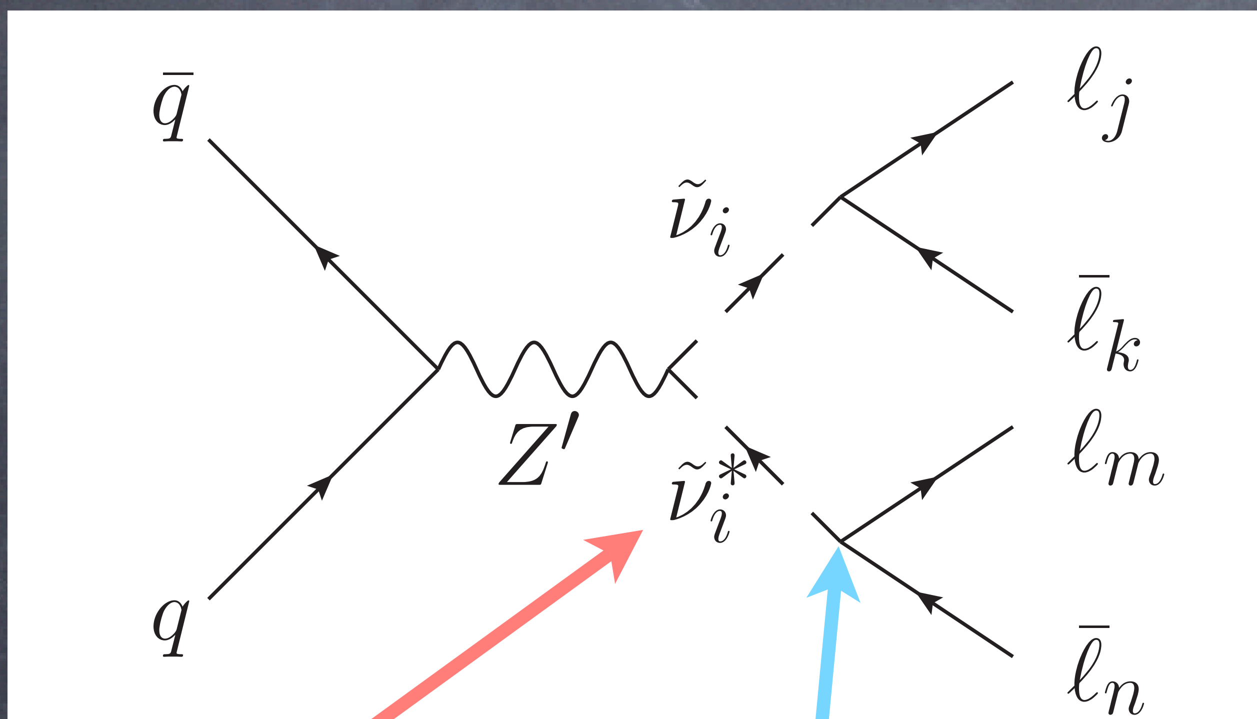
Use various leptonic(e, μ) Z′ resonances
for new physics search.

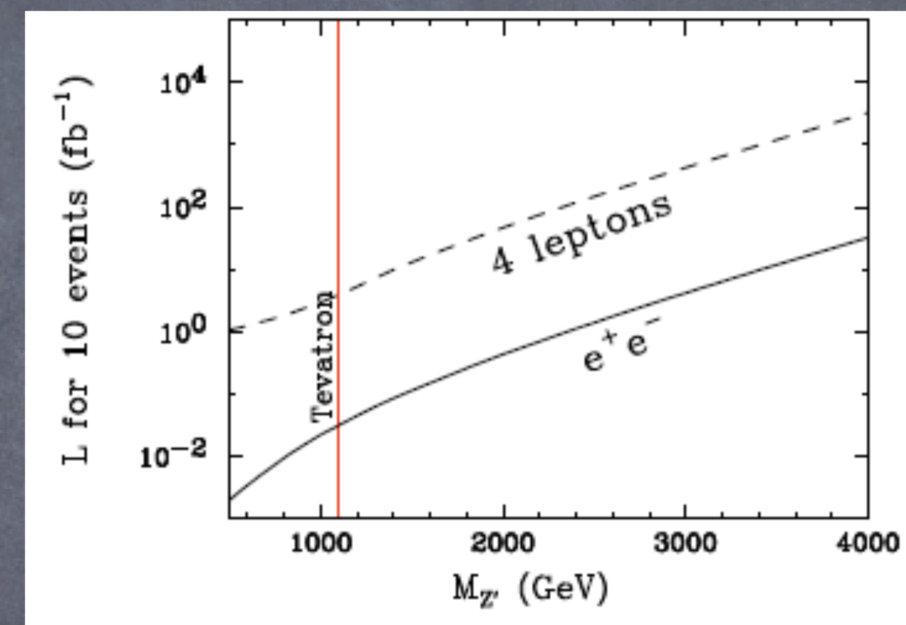


new particle
(superpartner, Higgs)
in the middle

4 lepton Z′ resonance
: SUSY search (for sneutrino LSP case)

HL [2008]





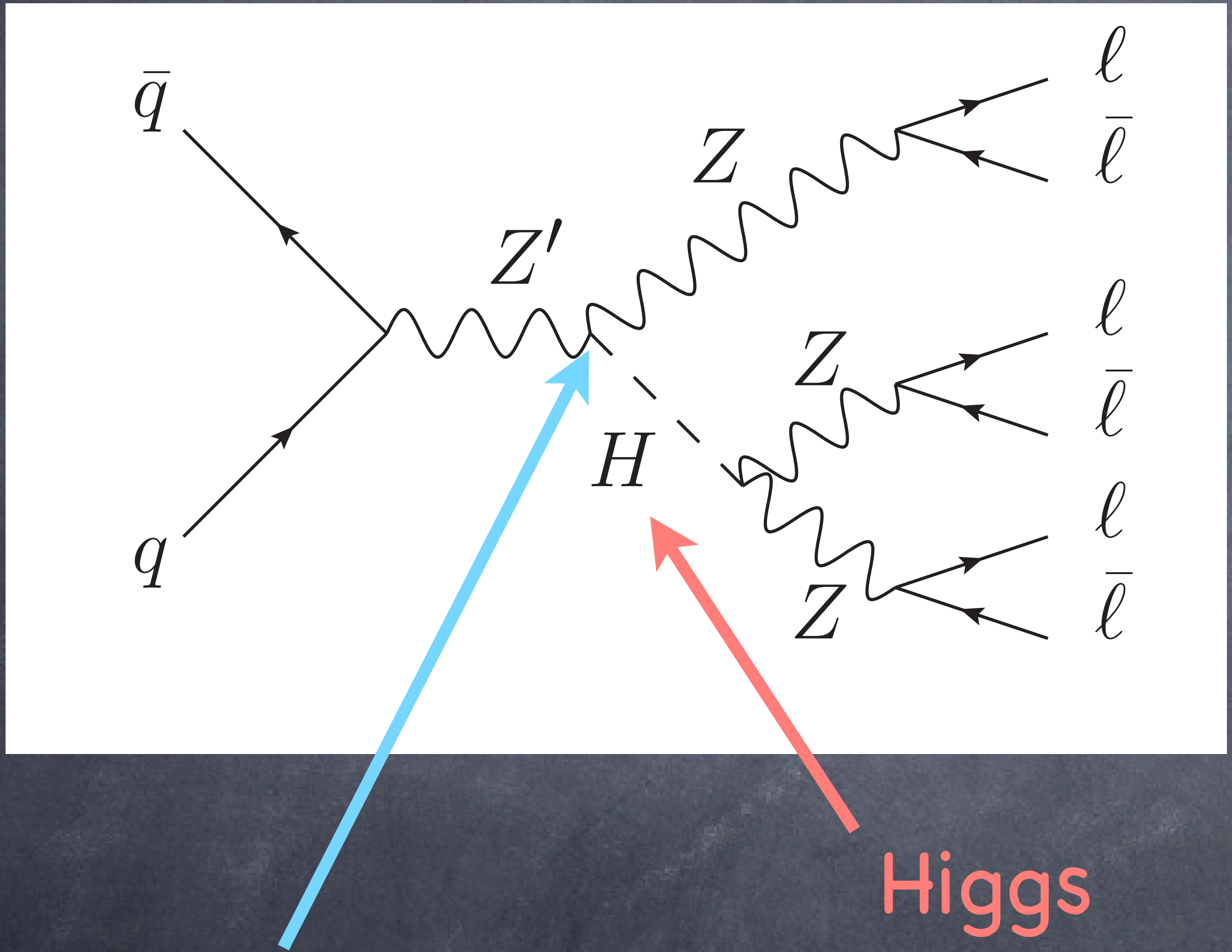
superpartner
(sneutrino)

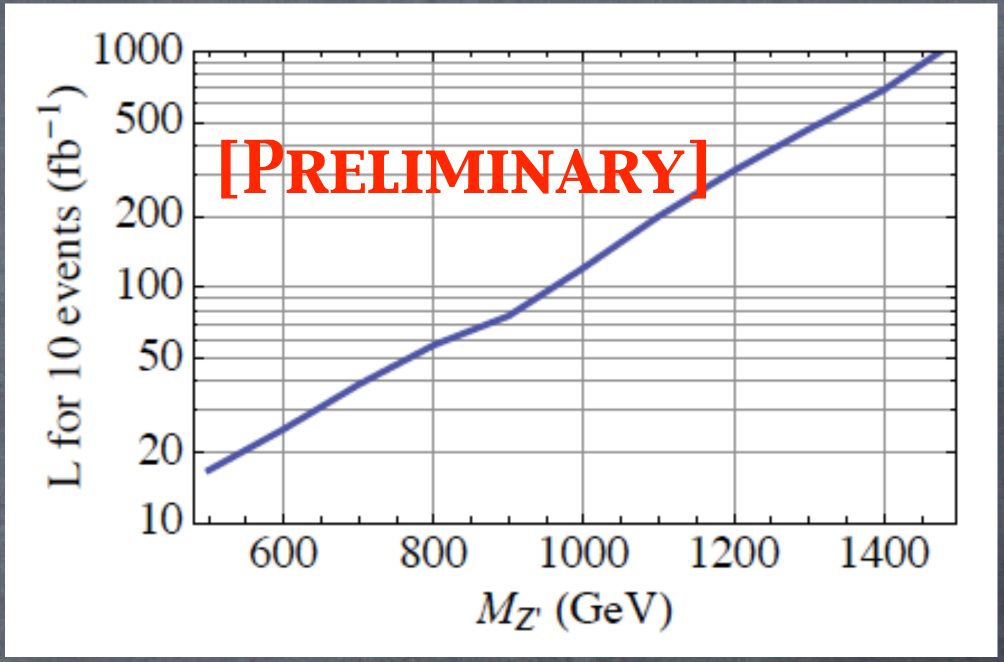
(ex) L=13 fb^{-1} for $M_{Z'}$=1500 GeV
[Details omitted]

L violating coupling (λLLE^c)
(Scalar neutrino LSP decays to SM particles)

6 lepton Z′ resonance
: Higgs search (regardless of SUSY)

[in preparation]





(ex) L=40 fb^{-1} for $M_{Z'}$=700 GeV
[Details omitted]

Z′-Z-H coupling can be sizable if Higgs has U(1)′ charge.
(longitudinal mode of Z = imaginary part of H)

Works for even leptophobic Z′

Summary

1. Motivation

Higgs -> SUSY -> U(1)′

2. TeV scale U(1)′ is a good SUSY companion symmetry (to stabilize proton and dark matter) alternative to R_p.

3. LHC implications (various leptonic resonances)

2L resonance at $M_{Z'}$: Z′ search

4L resonance at $M_{Z'}$: SUSY search (sneutrino LSP)

6L resonance at $M_{Z'}$: Higgs search ($m_H > 2M_Z$)

TeV scale U(1)′ is well-motivated, and can help searching for major discovery goals (Higgs, SUSY) at the LHC.